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Determining the feasibility of a method for improving bandwidth utilization of cable networks

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ABSTRACT

While the cable television industry has made significant investments in infrastructure to improve the number and quality of services delivered to their end customers, they still face the problem of limited bandwidth of signals down "the last mile" of coaxial cable to the subscriber premises. This thesis investigates an approach devised by the author to overcome this limitation. The method involves clustering of channels in both the upstream and downstream directions in a DOCSIS compliant cable system. A model of this approach is made and the theoretical maximum throughput is calculated for several scenarios. Results are compared to performance of existing systems. It is found that proposed approach yields significantly more throughput for a given RF bandwidth than others in the comparison.

Chapter 1: Introduction

While cable television began its life with antennas and coaxial cable in the late 1940's, it was not until the Cable Act of 1984 that increased investment in cable industry infrastructure began to grow rapidly. Since then cable companies have expanded their offerings to include digital, high definition and on-demand programming, data networks, and telephone. Most companies have invested in optical fiber transmission and digital infrastructure. The fundamental limitation of cable companies today, however, is that "the last mile" is still coaxial cable, and such cable has a limited radio frequency (RF) bandwidth for transmission of signals. The reason that the bandwidth of coax is even relevant is that it is a shared medium for the subscribers in a given neighborhood and many television signals are being sent down the wire whether or not they are being watched by subscribers.

Cable companies have considered several techniques to get around this bandwidth limitation. Most cable networks started with a bandwidth of 500 MHz and then upgraded to 750 MHz as the demand for improved programming pushed the limits of the existing systems and suppliers responded with equipment for 750 MHz. This upgrade came at a great dollar cost to the cable companies, but competition for subscribers with satellite companies made such an investment mandatory. Now the industry is weighing an upgrade to a 1 GHz infrastructure; some have already begun implementation. According to experts in the field, this upgrade by itself will not solve the bandwidth problem (see literature review below for further details.)

To avoid confusion it is important to understand the difference between how cable companies deliver their services and how telcos deliver their services. Cable companies have traditionally delivered video over coaxial cable (and more recently over fiber optic lines) using radio frequency signals. When cable companies want to deliver data over these same lines they must do so with RF using a standard such as Data Over Cable Service Interface Specification (DOCSIS). Telcos such as AT&T and Verizon have delivered voice (analog and digital signals) over copper (and more recently over fiber optic). When telcos deliver data over copper voice lines, they do using one of the Digital Subscriber Line (DSL) specifications, which take advantage of the broad bandwidth that the copper voice lines can carry and is not being utilized for voice communication. Over fiber optic lines, Verizon uses FiOS (Fiber to the Home) for data transmission as well as video and telephone. This system depends on different wavelengths of light transmitted through the fiber to separate the various services. AT&T uses VDSL (trademarked as U-verse), which is fiber to the neighborhood and then copper to the home for data, video, and telephone service. Telcos send video using Internet Protocol, i.e. IPTV. Cable companies can send video both over RF and through their data channel as IPTV.

Chapter 2: Cable Architecture

2.1: Existing Cable Networks

To better understand the bandwidth issues it is helpful to review the architecture of the cable network. Cable companies (hereafter referred by the industry acronym, MSOs – multiple system operators) collect content at three levels: nationally, regionally, and locally in what are known respectively as a super headends (SHE), regional headend (RHE)/video hub office (VHO), and video switching offices (VSO). These are illustrated in figures 1 – 3. Appendix A provides a glossary of acronyms.

Content is received nationally in the SHE, usually from satellite and national broadcast feeds. Also, video-on-demand (VOD) servers receive video content from distributors. The content is encoded and distributed via core routers over an IP/MPLS core network to the VHOs. The VHOs are typically at the state or large metropolitan level (pop. ~ 100,000 – 500,000). Local content is aggregated at this level with the national content. Distribution occurs through the VSOs to the service area. It is at the video switching offices that connections are made through to the last mile where coaxial cable delivers the services. It is in this area that the rest of this research paper focuses.

A schematic of the “last mile” is shown in figure 3, where both DOCSIS and digital video are implemented. Digital video signals are sent through an Edge Router to an Edge-Quadrature-Amplitude-Modulator (EQAM), which converts the IP packets containing the video content to RF for transmission to the residential Set Top Box (STB). The DOCSIS packets are processed through the Cable Modem Termination System (CMTS) in both the downstream and upstream directions to/from a DOCSIS cable modem. The EQAM is located at a VSO. Connecting it to a neighborhood being serviced is Hybrid Fiber/Coax (HFC), which may be either fiber or coax. However, once at the edge of the neighborhood a fiber transmission line must pass through an optical node to be converted into an electrical RF signal that goes via coax to either the STB or a cable modem. If the transmission line is coax from the EQAM, then the coax may go through a series of drops directly to the end-user's STB or modem.

Up to the EQAM, bandwidth is not an issue because the transmission is all IP, and the MOS can afford to make the necessary investment in the relatively sparse infrastructure. Upon exit from the EQAM, current cable bandwidth is limited to either 750 MHz or 1 GHz due to cost considerations of the equipment as well as limitations in the transmission lines. A typical allocation of this spectrum is shown in figure 5. In this example the vast majority of the spectrum (~550 MHz) is occupied be analog TV signals; ~150 MHz is dedicated to digital video; 24 MHz to VoD; and only 12 MHz is available for high speed data.

Note that frequent use will be made of the term "bandwidth." In this document it has two distinct meanings. In one case it refers to the radio frequency bandwidth of an RF signal, as measured in hertz (usually megahertz in this document.) In another use the term refers to data bandwidth, as measured in bits per second (usually in mega bits/sec in this document.)

2.2: Literature Review

A review of the literature shows a large number of industry white papers and conference presentations, patents, and a few papers in refereed journals. Overviews of existing cable infrastructure are provided by Microsoft, Emmendorfer, and Ciena. Matarese and Breznick present an in depth analysis of the bandwidth/throughput problem that cable operators face with their current infrastructure. A good discussion of the options that exist for the “last mile” can be found in Tompkins, et al.

Proposed solutions to this looming problem are many and varied. Birkmaier discusses several different approaches in an overview of the industry. It is clear from the papers by Matarese and Bing and Lanfranchi that switched digital video (SDV) will figure into an intermediate if not long-range solution. Davis provides a good technical overview of the design considerations that go into SDV implementation. Matarese presents an overview of the migration from analog cable to video over IP. He shows how this migration generates additional available bandwidth. He presents architectures for various forms of SDV multicast, for example with DOCSIS and with Statistical Multiplexing (STATMUX). He also presents architectures for various forms of SDV unicast, including time-shifted TV. Infrastructure costs are examined for each type of architecture. Matarese presents video over IP, and one of his VOIP architectures uses the DOCSIS standard.

Bing and Lanfranchi explore the issues associated with the optimized implementation of SDV and video on demand (VOD) services for the DOCSIS 3.0 architecture. An essential feature of the DOCSIS 3.0 architecture is the combining of channels to obtain upstream and downstream data rates of 160 Mbps and 120 Mbps respectively. Like Matarese, Bing and Lanfranchi emphasize the advantages of efficient use of 256-channel Quadrature amplitude modulators (QAMs) in the physical layer using statistical multiplexing. They do, however, point out that the extreme complexity of this arrangement may make it more troublesome than the improvement in cost. They examine the impact of video program access patterns, rate-limited video smoothing, and scheduling policies on the costs of implementation. They propose a scheduling algorithm for situations where the request rate for particular programming exceeds the available bandwidth. They conduct an extensive evaluation of the algorithm using realistic assumptions about rates. They conclude that the repeatability of video program access patterns should allow for the use of efficient scheduling algorithms.

Emmendorfer conference presentation focuses on the implementation of DOCSIS 3.0 as the cost-effective and efficient solution for the cable provider. Cable Multiple System Operators (MSOs) have a complete infrastructure for the delivery of video, data, and telephone. The challenge is to increased data bandwidth without major system upgrades; that is, use the existing Network Access Layer equipment and Device Activation systems. According to Emmendorfer, DOCSIS 3.0 is the architecture that MSOs have chosen to achieve this increase in bandwidth. Emmendorfer considers the bandwidth implications of Hybrid Fiber Coax (HFC) and RF over Glass (RFOG). His conclusion is that both approaches can support data rates of at least 100Mbps.

G. Ireland addresses the use of current cable HFC technology to support IPTV. (IPTV is so attractive because it will allow for the delivery of individualized content to any device over any network.) An important feature of IPTV is that it is dynamic multicast, meaning that only content requested by viewers is sent over the last mile.

Ireland analyzes network capacity and concludes that capacity is of major concern to MSOs. He observes that SDV is the most likely solution to increasing bandwidth over HFC networks. One technical challenge is that IPTV is video and not data. As such, it is very bandwidth intensive, much more so than streaming video on the Internet. On the plus side is that once SDV is installed, IPTV is only a software upgrade away. Competing with this approach to delivering IPTV is the utilization of Cable Modem Termination System (CMTS), which is essential a data delivery service. Ireland goes on to consider the economic impact of the various approaches, making no predictions about what the cable companies will actually do.

Doverspike, et al. also provides a very good overview of the design considerations of an IPTV network. It gives very good information about the limitations of devices at various points in the system. It also explores reliability issues and how to provide backup and mitigation for problems.

Breznick also examines the role of SDV in solving the bandwidth crisis in cable networks. Unlike Ireland, Breznick's analysis takes into account the current infrastructure in various markets served by the major cable operators and what that means with regard to required future investment. He points out the investment in new infrastructure could make the costs prohibitive. One the major obstacles to the rollout of SDV that must be overcome is the lack of industry-wide acceptance of a standard for this technology. Breznick makes the point that one of the most attractive features of SDV is that it allows MSOs to use their bandwidth more effectively. However, it is also the case that only the digital channel portion of the cable spectrum can benefit from the increased effective utilization. The analog portion, which accounts for about 60% of the bandwidth, is not affected by this enhancement and must be "reclaimed" by other means.

A preliminary search of U.S. patents gives some insight into other solutions that have been invented to solve the bandwidth problem. The Majeti, et al. U.S. Patent 5,675,732 appears to come closest to the approach suggested in this research proposal. Their solution combines CCTV channels to get extra data bandwidth; however, they convert all data packets from a TCP/IP network to NTSC-compatible format so that they can be sent via normal TV format. Given that this patent was filed in 1995, it is not surprising that an IP-based solution was not proposed. Carr, et al. U.S. Patent 5,608,446 uses both a high bandwidth pipe for data transfer and a low bandwidth one for control purposes. Hoarty, et al. U.S. Patent 5,557,316 split bandwidth depending on function – one for regular broadcast and another for on-demand services. All of these approaches improve bandwidth utilization, but because of their filing dates are in the mid-1990, they do not anticipate the systems in place today.

Chapter 3: The Bandwidth Problem

3.1: The Cable Network Bandwidth Problem

In the conventional embodiment of current cable networks all analog and digital content is sent down the line to each STB regardless of whether the channel is being viewed. The only exception to this is the content that is carried through Video on Demand channels. Thus, based on the example cited above, the 750 MHz of bandwidth is occupied by:

Table 1. Illustrating Typical Cable Bandwidth Allocation

SIGNAL	BANDWIDTH	VIDEO CHANNELS
Analog Video Channels	500 MHz	~ 82Channels
Digital Video Channels	150 MHz	250 Programs or 75 HDTV Programs
Video on Demand	24 MHz	N/A
High Speed Data	12 MHz	N/A
Control Signals/Available	82 MHz	N/A
Total Bandwidth	748 MHz	

Assumptions: The above table illustrates a typical NTSC-compliant cable spectrum. Note that Euro-Cable (PAL) standards provide for an 8 MHz channel width instead of the 6 MHz in NTSC.

This example illustrates the limitations that MSOs face. In order to remain backwards compatible with older sets that a majority of their customers may have, they continue to send about 70 to 90 analog channels to every subscriber. They can send up to 75 HDTV channels or 250 digital channels (or some combination). That leaves a few 6 MHz slots for Video on Demand and only 12 MHz of data bandwidth to serve an entire neighborhood of typically 500 homes (but can be up to 2000 homes). The digital video content available to MSOs to distribute far exceeds the 75/250 channel limitation. Some satellite systems offer 1000 channels of content. Furthermore, 12 MHz of bandwidth is totally inadequate for 500 homes if they had multiple computers connected to their cable modems. (We can estimate the number of homes that can be serviced with two 6 MHz of bandwidth by assuming the cable company typically offers 12-15 Mbps for each household. A DOCSIS channel can support approximately 43 Mbps. If we assume that the line is fully subscribed, then each 6 MHz channel can support between 40 – 80 households. Two such channels can, therefore, support between 100 – 200 households. Clearly 500 to 2000 households would suffer degradation in internet service.) Consequently, MSOs are limited in the digital video content they can offer and the amount of data bandwidth they can support.

3.2: Commonly Proposed Solutions to The Bandwidth Problem

The only commonly proposed solution that utilizes the current physical infrastructure is Switched Digital Video. The other approach involves replacing the "last mile" infrastructure with optical fiber and is commonly called RF Over Glass (RFOG).

RFOG is a relatively new technology, having made its appearance in mid-2007, and according to Ross, it not yet standardized. There are other acronyms that are used to describe the technology. Motorola calls it Cable Passive Optical Network (CablePON). Cisco's Video Technology Group calls it DOCSIS PON. "The Society of Cable Telecommunications Engineers calls it Advanced Fiber Access and has started work on standards for it." (See Birkmaier.)

The concept of RFOG is fairly straightforward. The HFC network and its appropriate infrastructure are bypassed with fiber that terminates in the customer's premises in an Optical Network Terminator (ONT). The ONT connects to customer's equipment in the usual manner through the customer's cable modem and set-top box. In effect, the customer gets his DOCSIS signal directly from the cable operator's backbone. This bypasses the bandwidth-limiting infrastructure and permits offering high bandwidth directly to end-users.

Currently implementation has been limited to new builds where HFC systems would cost about the same as RFOG. Dense neighborhoods are cheaper to wire with HFC because in less dense areas signals running from the DOCSIS node to the customer premises requires amplification every 1000 feet. Thus less dense areas favor RFOG. Also commercial customers are getting RFOG because they demand increased bandwidth for their data needs.

Switched Digital Video (SDV) is a partial solution to the bandwidth problem that has been adopted by most of the MSOs. As previously described, in a standard cable network all content is sent down the "last mile" whether it is being viewed or not. In a SDV network only the channels actually being watched are sent downstream from the fiber node to the homes that are served by that node. See figure 4. In general this saves on bandwidth since in the majority of homes typically watch the same channels. Figure 5 shows a comparison of the 750 MHz spectrum of a conventional cable network and one with SDV.

In reality, MSOs still send the most popular digital channels to each STB regardless of whether it is being watched by that customer. These non-switched video channels relieve the network of control overhead. To view a switched video channel the

STB must send a command upstream to request that the particular channel be sent downstream to it for viewing.

There are a number of benefits of SDV to the MSOs. For one, its implementation is estimated at less than a half that of an infrastructure upgrade to a 1-GHz plant, and the implementation can be scheduled so there is little disruption and no inside-wiring changes for customers. Many customers are unaware of its implementation. It has been reported by Breznick that there is a 40% – 60% savings of the digital spectrum. This has enabled the addition of a much-needed (from a competitive viewpoint) 20 high-definition channels. Also cable operators have been able to upgrade one service group at a time to the newer MPEG-4 compression standard, which by itself frees up additional bandwidth (see below.)

The network architecture employed for SDV adds some complications to the operation of the system. SDV dynamically allocates a channel to a subscriber when that subscriber requests it. If a second subscriber being fed by the same node wishes to view the same programming, he just joins the stream. There is no further consumption of bandwidth. This allocation of a channel and the subsequent joining the stream requires new complexity in the upstream software compared to non-SDV cable.

Each program that is part of the switched portion of channels is encoded at a constant bit rate (typically 3.75 Mbps.) It is then encapsulated into IP packets for injection into the IP network as part of an IP multicast group. The EQAM treats these switched channels as standard IP multicast services throughout the network.

The decision as to how many switched versus non-switched channels in a given network is a complex one that depends heavily on the objectives that MSO is trying to achieve. Since it involves infrastructure (investment in narrowcast EQAMS), it is a decision that must be made prior to implementing SDV. There is a good exposition of this subject in the literature (Davis, 2007). At one extreme is minimal investment that frees up only the bandwidth required in the short term. The result is more tuners per service group and less spectrum freed up. Fewer service groups means lower investment in EQAMs. Optimized bandwidth gains means fewer tuners per service group and a heavier investment in EQAMs.

Having made the decision regarding the infrastructure, there remains the relatively dynamic decision of which programming to devote to the non-switched channels and which is a candidate for the switched channels. This decision involves understanding the viewing patterns of each of the service groups. The channels that are part of the non-switched block may vary both with service group and with the time of day. This adds another layer of complexity to the software that controls SDV.

There is another consideration in improving bandwidth utilization. Currently all cable systems use MPEG2 for video encoding (Bing). MPEG4 is more efficient in bandwidth utilization for the same picture quality. It does, however, require more processing in both the encoding and decoding of the video signal. This is generally accommodated with dedicated hardware chips that alleviate some of the burden. While there is a savings with MPEG4, no consideration is given to it in the comparison made below.

3.3: DOCSIS 3.0

DOCSIS is an acronym for Data Over Cable Service Interface Specifications and is an international standard developed for transmitting data over cable TV networks. DOCSIS was first developed by CableLabs in collaboration with companies participating in the cable industry. DOCSIS 1.0 was released in 1997, and virtually all cable networks have implemented one form or another of the early versions. DOCSIS 3.0 was released in 2006. The DOCSIS 3.0 Specification is comprehensive consisting of 5 separate documents. These are:

- Security Specification
- Cable Modem to Customer Premise Management Specification
- Physical Layer Specification
- MAC and Upper Layer Protocols Specification
- Operations Support System Interface Specification

The last two documents were only recently released – January 15, 2010. Most cable operators have plans to incorporate the latest release into their systems, but only a few have fully implemented DOCSIS 3.0.

DOCSIS 3.0 Reference Architecture is shown in figure 6. It is important to remember that DOCSIS only applies to the data channel portion of the cable network. These data channels are 6 MHz wide MPEG in the U.S. and may be located anywhere within the cable spectrum. RF modulation in both directions is provided via QAMs. In either the downstream or upstream direction both FDMA/TDMA and S-CDMA are permitted. The CM can advertise its capabilities to the CMTS. All configuration data is kept track of by the CMTS.

An important feature unique to DOCSIS 3.0 is the concept of channel bonding. The CMTS may dynamically designate as many channels as are available as a Downstream Bonding Group or an Upstream Bonding Group. The CM has multiple receivers and transmitters to utilize the entire set. Packets are given sequence numbers so that they may be reassembled after they are transmitted over multiple channels. For upstream transmission the CM requests bandwidth based on its needs from the CMTS, which may grant such a request using any number of appropriate channels within the Upstream Bonding Group. All control is handled by the CMTS.

Another important enhancement of DOCSIS 3.0 is additional support for IP Multicast. From the specifications these include:

- Source Specific Multicast traffic for IGMPv3 and MLDv2
- Support for bonded multicast traffic
- Provisions for QoS for multicast traffic
- Support for IPv6 multicast traffic including Neighbor Discovery and Router Solicitation
- Tracking of Customer Premises Equipment (CPEs) joined to a multicast group at the CMTS to aid load balancing
- Encryption of multicast packets using a Security Association communicated to a CM.

At the Network Layer level DOCSIS 3.0 requires the use of either IPv4 or IPv6 for transporting management and data traffic over the HFC between the CMTS and the CM. DOCSIS 3.0 also requires the use of the following protocols for management and operation of the CMTS and CM:

- SNMP
- TFTP – used by the modem to download software and configuration information
- DHCPv4/6 – used for passing configuration information to hosts on a TCP/IP network.

Chapter 4: Author's Approach to The Bandwidth Problem

Switched Digital Video achieves savings in bandwidth by using a smaller set of channels to send only those programs that are being watched down the line to the customer premises. In such a system a certain number of channels are designated for non-switched video channels with the remainder designated for switched video. Those channels not being used for video transmission may be designated for data bidirectional transmission. While the number of channels chosen to be in each subgroup may vary depending on the configuration, once a configuration is set, the number in each subgroup is fixed. Most commonly, the channels dedicated to data transmission are DOCSIS 3.0 compliant. In such a compliant system, these data channels may be dynamically combined in a way called "channel bonding" to offer more or less bandwidth to a particular subscriber. An illustration of what is meant by channel bonding in DOCSIS 3.0 can be seen in figure 7.

In one embodiment of the author's approach the number of channels devoted to analog video is fixed as before, or in a second embodiment is eliminated entirely, and the channels are all reallocated to digital channels. In either case, all non-analog channels are DOCSIS 3.0 compliant channels. All "broadcast" video programming is sent via IP Multicast. Video on Demand is sent via IP Unicast.

The spectrum is logically split into two blocks of DOCSIS channels: The Video Group (TVG) and The Data Group (TDG). [This Group includes Internet and Voice Services] While these channels may be contiguous, it is not necessary that they are. Sufficient channels are assigned to the TVG to handle all video needs plus a buffer to cover burst requirements. As more channels are needed for video, they are reallocated from TDG. When channel bandwidth is no longer needed in TVG, channels are allocated back to TDG. In this way the maximum amount of bandwidth is utilized to service CPE. This reallocation is shown diagrammatically in figure 8 along with a comparison to the more common SDV implementation used currently by some MSOs.

The reasons that two groups, TDG and TVG, were chosen relate to QoS and its limitations. Video delivery is such an important part of the supplied service that the author chose to segregate it from the data delivery. Had the transmissions not been divided, it would have been necessary to employ QoS to attempt to provide some guarantee delivery of video services. While QoS may work well when there are bandwidth limitations, in this case the author felt that less than satisfactory delivery would be achieved.

A number of refinements need to be made in figure 6 in order to incorporate the author's approach. One important addition is a device fed by the cable modem at the customer premises that converts IP video data into a compatible format for viewing on a standard TV. This could be thought of as a sophisticated version of the STB. Note that DOCSIS 3.0 protocols are backward compatible with earlier versions of DOCSIS, so legacy CMs will still function for downstream and upstream data transmission. Such a device is shown in the diagram in figure 7.

Another big change is the software that resides within the CMTS and its associated control systems. This provides the ability to tailor ads to the individual viewer.

Chapter 5: Comparison Of The Various Approaches

5.1: Bandwidth Comparison

Several comparisons can be made of the approaches discussed above. The simplest method is to assume that there is a full complement of analog channels (occupying 500 MHz of bandwidth) and all special services are ignored. The resulting 204 MHz is then allocated to digital video programming. (See Table 1 above.) For the purposes of this comparison it is assumed that the number of HDTV program channels is approximately 35 % of the SD programming channels. This is consistent with what was found on actual Time Warner and Cablevision websites (See Appendix B.) In the case of conventional cable and SDV it is assumed that 10 SD program channels or 3 HDTV channels can fit into each 6 MHz block of spectrum. To calculate the number of digital programming channels for the conventional cable system is straightforward.

Let

N_{SD} = the number of channels containing standard definition programming

N_{HD} = the number of channels containing high definition programming

Then

(1) $N_{SD} + N_{HD} = 34$

Based on other considerations we want the number of high definition programming channels to be equal to 35% of the number of standard definition programming channels. Since 10 standard definition programs can fit into a single 6 MHz channel and 3 high definition programs can fit into a 6 MHz channel, this gives:

(2) $3\ N_{HD} = 0.35\ (10\ N_{SD})$

Combining (1) and (2) gives

(3) $3\ (34 - N_{SD}) = 0.35\ (10\ N_{SD})$

(4) $N_{SD} = 15.7 \approx 16$

$N_{HD} = 18.3 \approx 18$

Translating into the number of programming channels gives:

Std. Def. Programs = 160

High Def. Programs = 54

The results for these two approaches are shown in Table 2 below.

The calculation of the number of program channels that fit into the 204 MHz spectrum is a little more complicated. The 204 MHz corresponds to 34 DOCSIS 3.0 channels. Each channel can support 38 Mbps, so the total bandwidth that is available is 1,292 Mbps. It takes 6 Mbps to transmit an HDTV program (see Doverspike) and 1.25 Mbps for a SD program. Again, assuming that the total bandwidth of HDTV programs is about 35% of that of SD programs, gives the equations:

$6\ N_{HDTV} + 1.5\ N_{SD} = 1292$

$6\ N_{HDTV} = 0.35\ (1.5\ N_{SD})$

This yields N_{SD} =360 SD program channels and N_{HDTV} =125 HDTV program channels. This is an increase in capacity of approximately 300% over the conventional cable network approaches.

Table 2. Comparison of Digital Channel Capacity of Three Approaches

SIGNAL	CONVENTIONAL CABLE	SWITCHED DIGITAL VIDEO	AUTHOR'S APPROACH
Analog Video Channels	~82 Channels	82 Channels	82 Channels
Digital Video Channels	160 SD Programs + 54 HDTV Programs	160 SD Programs + 54 HDTV Programs	360 SD Programs + 125 HDTV Programs
Video on Demand	*	*	*
High Speed Data	*	*	*
Control Signals/Available	*	*	*
Total Bandwidth	748 MHz	748 MHz	748 MHz

* For the purposes of the calculations these special services/functions were ignored.

Based on the above, it is clear that choosing an approach where all digital channels are DOCSIS channels yields a large increase in capacity to deliver additional programming. It is instructive to examine a more realistic scenario to appreciate the type of improvement that can be realized. The following scenarios are based on realistic examples presented in a white paper by Sinha and Oz. Details of these calculations are found in the Appendix B.

Table 3. Bandwidth Required to Deliver Maximum Channels for a Node

Node Size (Homes)	150	150	500	500	4x150	4x150	4x500	4x500
Number of Channels	500	500	500	500	500	500	500	500
Avg. Active Users %	23%	12%	23%	12%	23%	12%	23%	12%
Avg. Active Users	35	18	115	60	138	72	460	240
Max. Channels Required	19	12	55	31	69	36	187	120
Hi Def. Channels	6	6	14	8	17	9	47	30
Std. Def. Channels	13	6	41	23	52	25	140	90
Bandwidth Required	55.5 Mbps	46.5 Mbps	145.5 Mbps	82 Mbps	180 Mbps	106.5 Mbps	492 Mbps	315 Mbps

To understand what the "Bandwidth Required" numbers mean, it is necessary to go back to the size of the "pipe" that the MOS invested in for infrastructure. It is also important to recognize that at this time all U.S. MOSs are distributing the full complement analog broadcast channels. The table below summarizes the situation:

Table 4. Implications of Bandwidth for Various Infrastructure RF Bandwidths

	750 MHz Bandwidth	**850 MHz Bandwidth**	**1 GHz Bandwidth**
Analog Channel Bandwidth	495 MHz	495 MHz	495 MHz
Overhead per above	51 MHz	51 MHz	51 MHz
Remaining Bandwidth	204 MHz	304 MHz	454 MHz
Equivalent Bandwidth Mbps*	1292 Mbps	1925 Mbps	2875 Mbps
Node Size/Remaining Bandwidth			
150 min	1236.5 Mbps	1869.5 Mbps	2819.5 Mbps
150 max	1245.5	1878.5	2828.5
500 min	1146.5	1779.5	2729.5
500 max	1210	1843	2793
4x150 min	1112	1745	2695
4x150 max	1185.5	1818.5	2768.5
4x500 min	800	1433	2383
4x500 max	977	1609	2559

It is clear from the above table that the author's approach has significant bandwidth remaining that can be utilized for special video services such as VOD and for data transmission. It can also be seen that the smaller the node size the more bandwidth is available for other services. Obviously, the larger the "pipe" in the infrastructure, the more bandwidth that is available.

5.2: Cost and Time To Implement Comparison

The cost and time to implement switched digital video is documented in a brochure and video by BigBand Networks. They state that it is possible to do the conversion to SDV in 90 days. They provide a project plan, which shows how to accomplish this. The cost they quote is given as a cost per homes passes. A more relevant cost is the comparison of going SDV versus upgrading to a 1 GHz bandwidth infrastructure. Here their claim is that SDV is one-tenth the cost of an infrastructure upgrade.

The author’s approach is more difficult to estimate time and cost to implement. Without a realistic simulation, there is no estimate of the packets per second and the amount of bandwidth needed for the services that would be delivered. These will determine the cost and complexity of the CMTS required. There is also the requirement to provide new capabilities in the set top boxes to enable them to convert the video into a form viewable on customer-supplied televisions. The total cost is almost certainly more than SDV, but probably less than a full infrastructure upgrade to 1 GHz. Implementation times are definitely greater than SDV, and there will be more service disruptions until the complete system is up and running. With the additional costs and implementation of the author’s approach, there come the significant benefits for both the MSO and the customer.

Chapter 6: Future Directions

6.1: The Future of Cable Networks

To predict the future is always fraught with difficulty, but there exist trends in the cable industry that point the way to what is likely to happen over the next few years. Analog broadcasts have existed since the inception of television. Their future is limited; I think they will be phased out completely within the next few years. Commercial video will be all-digital through the CSE.

For MSOs to survive they must be cost-competitive with telcos and satellite providers as well as offering comparable services. This means moving to full IPTV with bidirectional data transmission speeds that only can be achieved by taking advantage of DOCSIS channel bonding capabilities to their fullest. MSOs will be forced to offer "personalized" video services, which means having the capability to deliver video by both unicast and multicast IP. To generate the necessary revenue they will be required to offer advertisers the ability to target ads at the individual level using unicast ad servers. Undoubtedly, FTTH or RFOG will be required in the last mile to support the more heavy use of the MSOs' services.

Certainly the biggest MSOs will be required to make the substantial investment necessary to achieve 1 GHz bandwidth capability. Whether some of the smaller units will need to is still an open question. Enough capability may be achieved through the adoption of IPTV and DOCSIS 3.0 data capability that the upgrade will prove unnecessary in the short term.

6.2: Future Directions for This Thesis Research

There are a number of directions this work can take. One of the more obvious next steps is to perform a simple but more realistic simulation of a cable network using various approaches to the bandwidth problem. Such modeling could include the addition of noise (see Al-banna) and a more realistic picture of the viewing habits of a typical audience. To get the latter information would require cooperation from organizations like Nielsen or CableLabs or one of the MSOs.

The simulations could be performed using OPNET or taking advantage of one of the services offered by BigBand Networks. It is possible either will permit limited use of these simulation tools by an academic institution for a specified period of time. Otherwise, the cost could be prohibitive.

It would be also interesting to discuss with some of the major suppliers to the MSOs the technical, cost, and operational tradeoffs of the available equipment that is necessary to achieve the maximum performance today.

Another interesting direction for the research to take would be to investigate the protocols that are currently in use in various parts of the system. Some of these protocols may be in use because of legacy considerations. If so, what are the best choices of protocols at each point in the network if the MSO could start with a clean sheet installation?

Any or all of these topics could convert this Masters Thesis into a rich, doctoral research project that could possibly contribute significant knowledge to the cable networking field.

Chapter 7: Conclusion

This paper investigated a number of ways that cable companies can increase the bandwidth available to them in order to be able to deliver additional services that will keep them competitive with satellite companies and telcos. It is seen that an upgrade to a 1 GHz infrastructure by itself does not provide as much bandwidth as other approaches. Switched Digital Video provides additional capability for data. However, it is not until video is delivered as IP over DOCSIS 3.0 in which dynamic channel bonding is employed – the author's approach – that maximum increases in utilization of existing bandwidth are achieved.

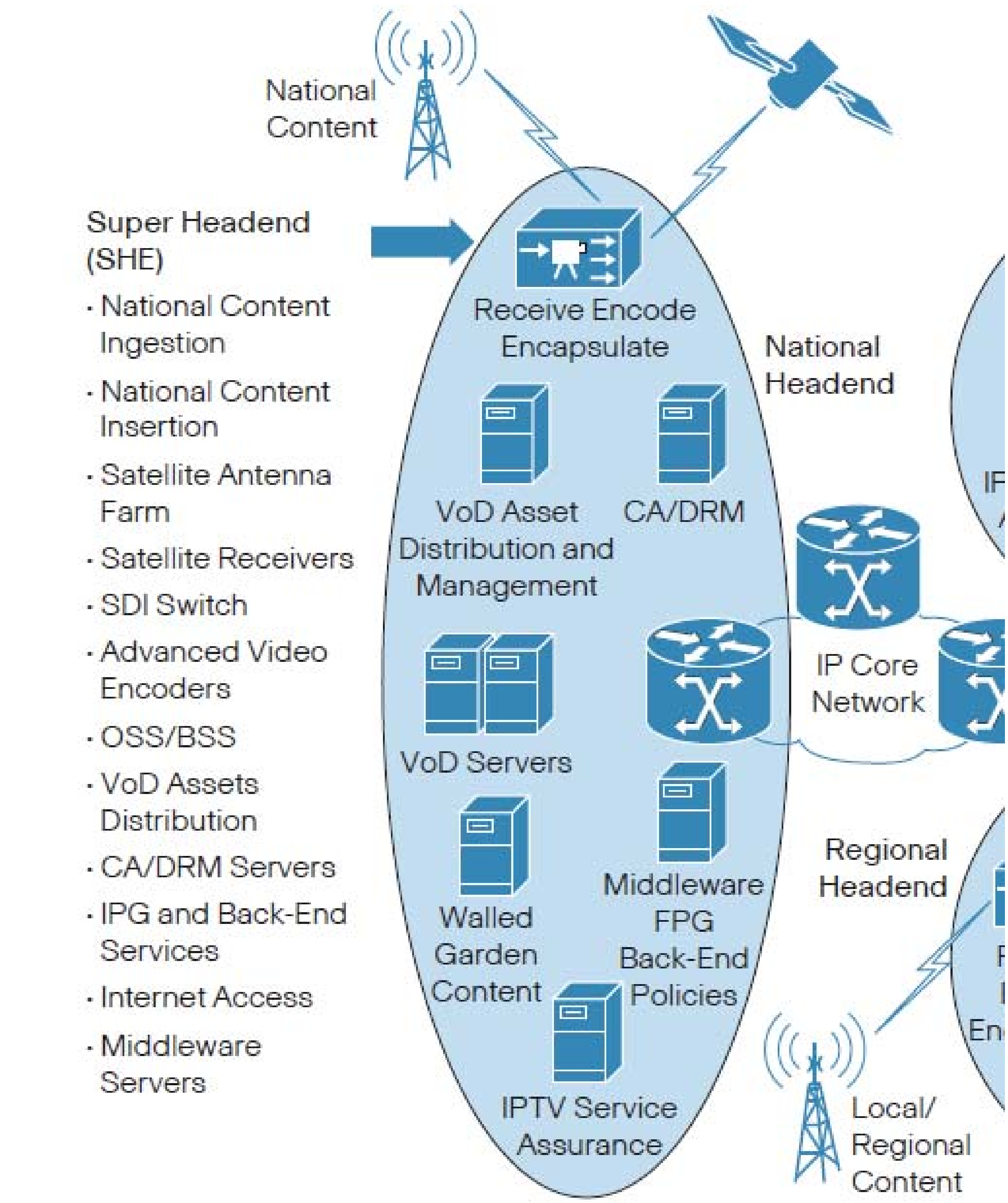
Little consideration has been given to cost and potential service disruptions in examining these different approaches. According to the literature (BigBand Networks), an upgrade of the infrastructure to 1 GHz is the most expensive step, as it involves the replacement of nearly all of the equipment in the Video Switching Offices that transmit over HFC and downstream to the customer premises. Adding Switched Digital Video to an existing infrastructure may involve some replacement of equipment in the VSOs and replacement of STBs. There are approaches, however, to accomplishing this switchover quickly and with minimum disruption of service (BigBand Networks). There is a tradeoff in that SDV is more complex, and there are more things that can go wrong. The author's approach using DOCSIS 3.0 is more complex yet, but it does offer the most gain in available bandwidth.

The logical extension of this research paper is a comparison of the various approaches using one of the industry standard simulation programs to test the practical limits of each. Such an undertaking is a large effort, as each major component from the

VSO through to the customer premises must be modeled using typical parameters. It would then be logical to fold in typical costs for each approach in order to do a cost/benefit analysis. Clearly such an analysis is beyond the scope of this paper.

FIGURES

Figure 1. Superheadend Cable Installation.



Adopted from Cisco IPTV Video Headend Brochure

Figure 2. Diagram Showing Regional and Metro Network

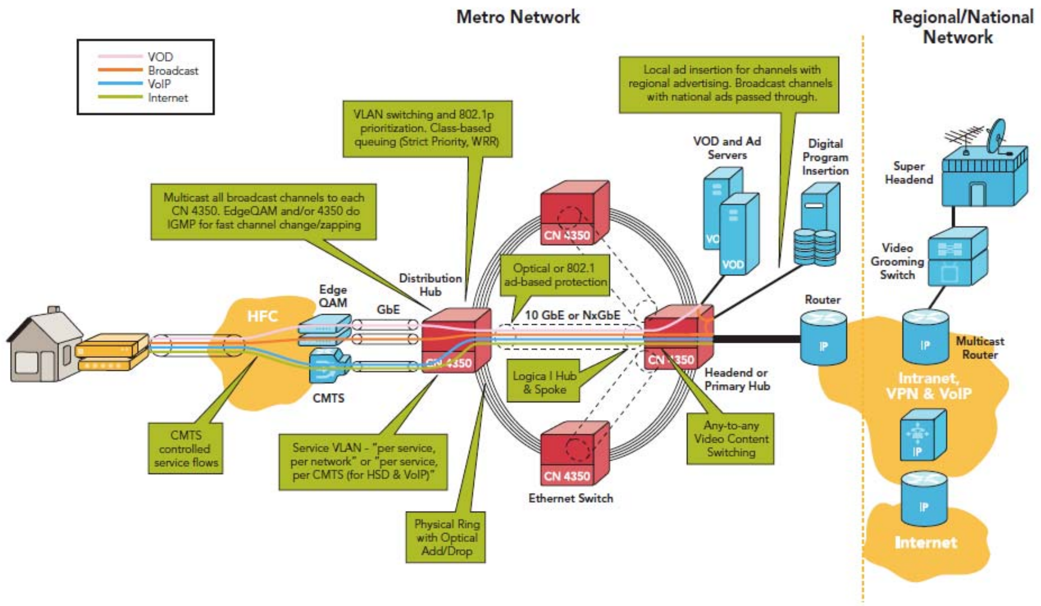


Figure 3. The "Last Mile" Showing Both Video and DOCSIS

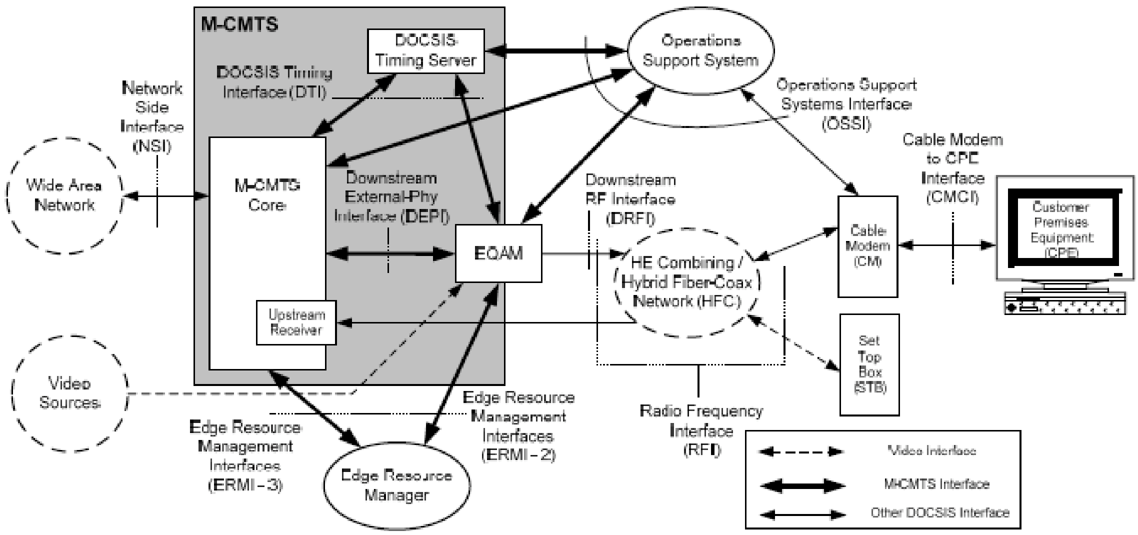
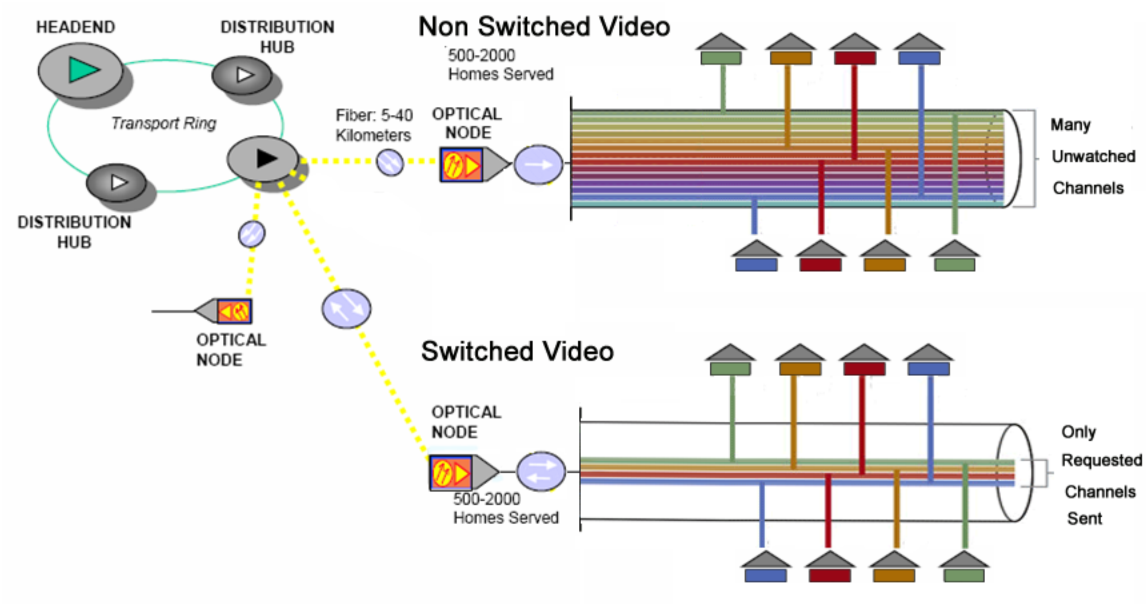


Figure 5-3 - M-CMTS Reference Architecture

|← LAST MILE →|

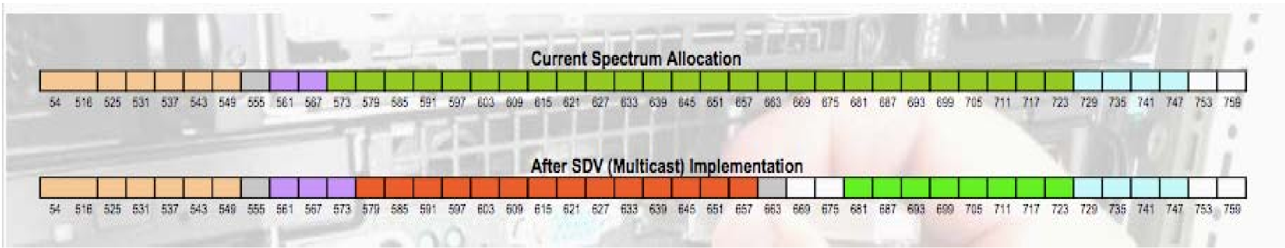
Adopted from DOCSIS Technical Report on EQAM Architecture

Figure 4. Switched Digital Video [Footnote]

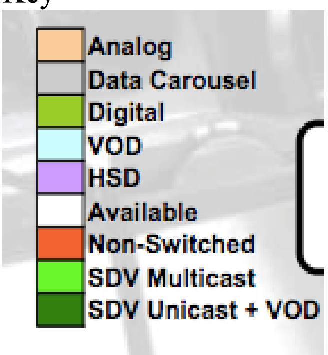


Taken from
http://upload.wikimedia.org/wikipedia/commons/5/51/HFC_Network_Diagram.svg

Figure 5. Comparison of the 750 MHz Spectrum of Conventional Cable and Cable with Switched Digital Video



Key



Adopted from Matarese

Figure 6. DOCSIS 3.0 Architecture

CM-SP-CMCIv3.0-I01-080320 Data-Over-Cable Service Interface Specifications

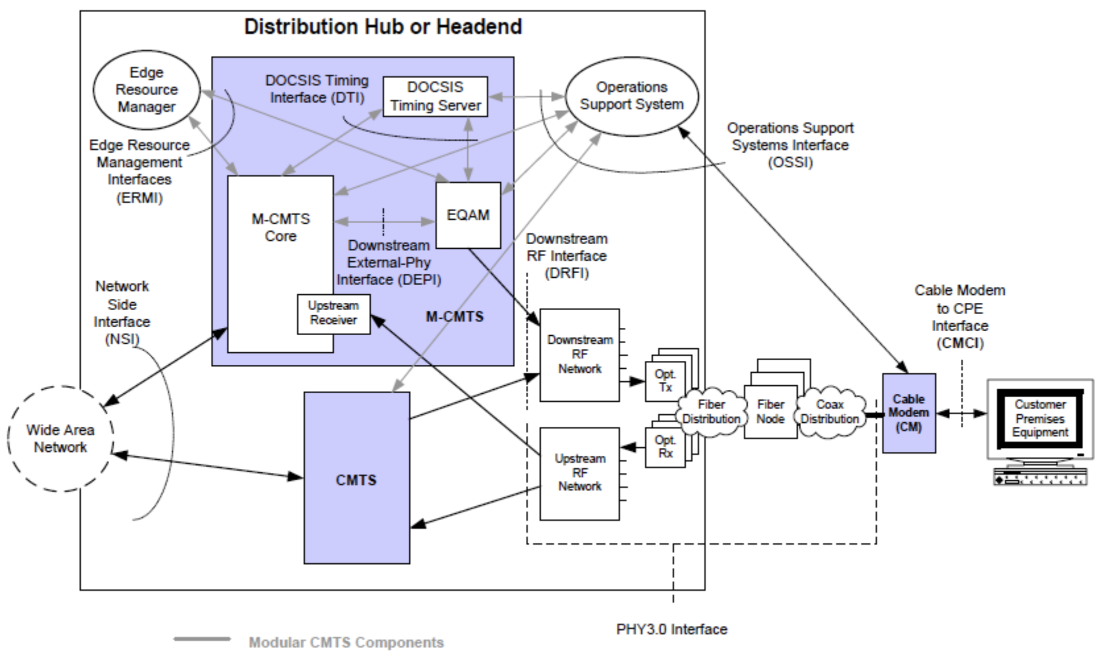
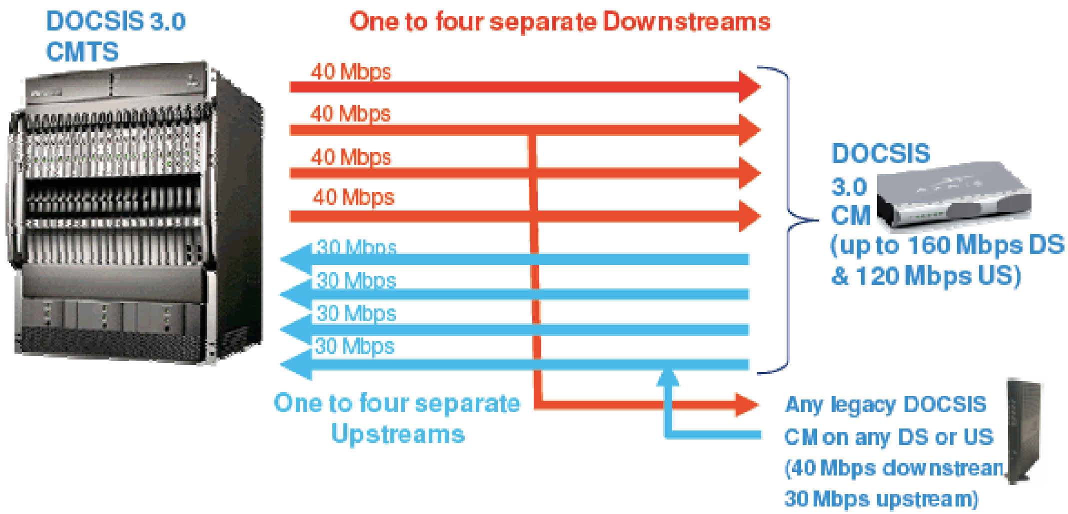


Figure 5-2 Data-Over-Cable Reference Architecture

Taken from DOCSIS Specification of the Physical Layer

Figure 7. DOCSIS 3.0 Channel Bonding

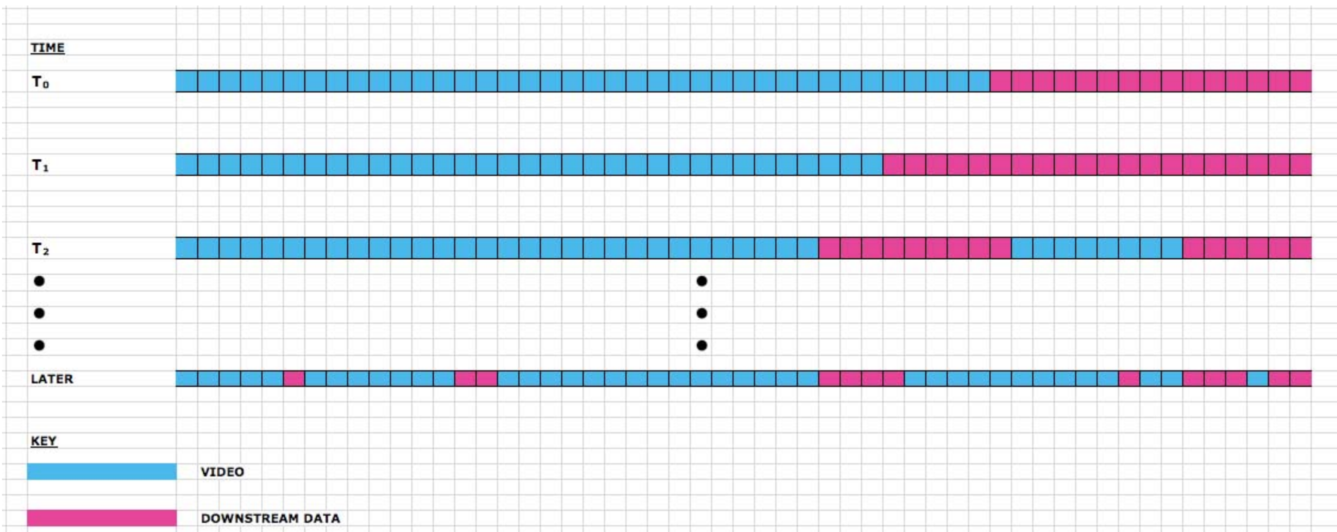


Taken from A. Al-Banna, et al.

Figure 8. An Illustration of the Author's Approach

AUTHOR'S APPROACH (All Channels are DOCSIS 3.0)

Note: No Analog Channels



APPENDIX A

Glossary of Cable Acronyms

Cable PON	Motorola's name for Cable Passive Optical Network
CM	Cable Modem
CMTS	Cable Modem Terminal System
CPE	Customer Premise Equipment
DOCSIS	Data Over Cable Service Interface Specification
DSL	Digital Subscriber Line
EQAM	Edge Quadrature Amplitude Modulator
HFC	Hybrid Fiber Coax
IPTV	Internet Protocol TV
MSO	Multiple System Operators
ONT	Optical Network Terminator
PON	Passive Optical Network
QAM	Quadrature Amplitude Modulator
RF	Radio Frequency
RFOG	Radio Frequency Over Glass
RHE	Regional Headend
SDV	Switched Digital Video
SHE	Super Headend
STB	Set Top Box
TVD	The Video Group
TVG	The Data Group
VHO	Video Hub Office
VOD	Video on Demand
VSO	Video Switching Office

APPENDIX B

Data and Calculations to Support Bandwidth Comparison

Data taken from "The Statistics of Switched Broadcast", Sinha and Oz, SCTE 2005 Conference on Emerging Technologies.			
	RAW DATA		**DERIVED DATA**
TRIAL A			
Total Homes Passed	4000		
Nodes*	4		

Digital Subscribers	603		
Number of Channels Offered	60		
Avg. no. of Active Viewers	140	603	23%
	98	450	22%
	60	300	20%
	30	150	20%
Average Active Viewers			21%
		Viewers	% Channels Viewed
Number of Channels Viewed	18	150	30%
	31	300	52%
	40	450	67%
	50	603	83%
TRIAL B			
Total Homes Passed	4000		
Nodes*	4		
Digital Subscribers	915		
Number of Channels Offered	171		
Avg. no. of Active Viewers	108	915	12%
Number of Channels Viewed	54		32%
Predicted Max. Channel Viewed			
Channels Offered	500	1000	1500
Channels Viewed	187	267	352
Percentage	37%	27%	23%
NOTE: In these trials the nodes were combined for the purposes of gathering statistics.			
Thus the maximum node size was effectively 4000 homes passed.			
From Nielsen Ratings			
The top 5 channels command approximately 42 % of all viewership.			
The top 10 channels command approximately 65-70% of all viewership.			

The raw data in the above table was extracted from the figures presented in the white paper report cited at the beginning of the table. The information from Nielsen Ratings was taken from their website. It was only used to confirm what I was seeing in the data from Sinha and Oz, 2005.

The rules that I used to calculate the bandwidth required are somewhat complicated. Based on the Nielsen ratings, I assumed that the minimum standard definition TV channels that would be viewed is six, and that anyone who had a high definition TV set would probably view these channels in high definition. A telephone call to the Senior Vice-President of Communications of CableLabs, Mike Schwartz, revealed that the number of homes passed per node varied all over the map for various MOSs. Further the number of active digital set top boxes that were actually viewing a program at a given time also varied widely across the country. As a result I chose to do a min/max type calculation using the two percentages (23% and 12%) of STBs in actual use at a given time based on the two datasets that were in the cited white paper. I also did a calculation for various node sizes, again based on the data.

The determination of the number of unique channels being watched at a given time is where the real complexity came in. When the calculations predicted that the actual number of viewers was large (see table in main body of text), I used the maximum channels required taken from the data in the Sinha-and-Oz 2005 reference. When the actual number of viewers turned out to be very small, I used the 12 channels cited above as the minimum number of channels to be viewed. In between these extremes, I used 50% of the number of viewers as the number of distinct channels being watched. The data in the white paper and the table above support this assumption.

To calculate the bandwidth required for a given number of distinct channels watched, I assumed that 25% of the total channels were high definition channels and the remaining 75% were standard definition. For high definition channels I assumed that the bandwidth required was 6 Mbps and for standard definition I used 1.5 Mbps.

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